

**HYDROLOGICAL WATER BALANCE AND FLOOD MANAGEMENT
STUDY FOR GANGA RIVER BASIN UNDER A RANGE OF
PROJECTED CLIMATE SCENARIOS**

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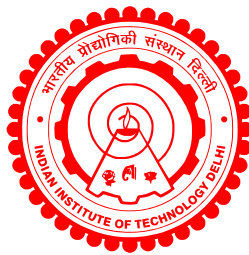
by

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Submitted

**In fulfilment of the requirements of the degree of Doctor of Philosophy
to the**



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CERTIFICATE

This is to certify that the thesis, entitled “*Hydrological Water Balance and Flood Management Study for Ganga River Basin Under a Range of Projected Climate Scenarios*”, being submitted by Mr. Jatin Anand to the Indian Institute of Technology, Delhi for the award of Doctor of Philosophy, is a record of bonafide research work carried out by her under our joint supervision. The thesis work, in our opinion has reached the standard, fulfilling the requirements for the said degree. Further, we certify that this submission is Mr. Jatin’s own work and that, to the best of our knowledge and belief, it contains no material previously published or written by another person which to a substantial extent has been accepted for the award of any other degree or diploma of any University or Institute, except where due acknowledgment has been made in the text.

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Jatin Anand

ABSTRACT

The Ganga River basin is one of the most populous river systems in the World. The river is of high importance with an estimated 440 million people directly or indirectly depending on the water that the Ganga and its tributaries provide for agriculture, drinking, hydropower generation, and navigation and for ecosystem services. The perpetual population increase and consequent water resources development has affected the river's flow regime which, in turn, has impacted the water availability, quality of water and thus, riverine ecosystems.

The availability of water has become an intriguing issue for irrigation systems, food security and ecosystem health. The availability of freshwater has been recognized as a global issue, and the reliable evaluation and quantification of it within the individual basin is necessary to bolster the sustainable management of water. Moreover, the negative impacts of climate change have been felt over wide range of spatial scales, ranging from small basins to large watersheds, which can possibly be detrimental to the services that natural water systems provide to the society. In addition, conflicts between increasing irrigated agricultural area, commercial crops, shifting cultivation and ever increasing domestic and industrial demand has already been a cause of tension in the society over water in the Ganga River basin, India. At present, with the ongoing advancement of social economy and requirement of water, the water resources shortage problem has worsened, and the operation of reservoirs, in terms of consumption of flood water, has become significantly important.

Application of physical based hydrological modeling has become imperative for planning and management of water resources. However, these models need to be calibrated and validated before it can be used further for scenario generation and assessment of various watershed management practices. In this study, a basin-scale hydrological model for the Ganga River basin has been developed to simulate the various hydrological processes using the Soil and

Water Assessment Tool model. Model validation using observed discharge series showed that simulated results were consistent with the observed data in reproducing the seasonal dynamics of surface water and suggest that the model is capable of reproducing the main hydrological features of the Ganga River basin including the snow and glacier melt. The study indicated that the annual average precipitation, net water yields and actual evapotranspiration of the whole basin were 1,167.5 mm, 601.6 mm and 496.5 mm, respectively. However, there are large variations in both temporal and spatial distribution of these components. Statistical methods (the Mann-Kendall, the Spearman's Rho, and the Student's t) have been used for detecting trends and gruesome change in streamflow simulated using SWAT model over the Ganga River basin and its sub-basins. It has been found that although the streamflow from the snow fed areas of the basin and also at the final outlet of the basin (taken at Farakka in the study) have increased, whereas the stream flow in the lower reaches and the non-perennial tributaries have declined significantly. This decline may be attributed to both anthropogenic activities and exogenous changes. The study indicates that there has been a substantial reduction in overall water resources availability with respect to Virgin scenario in the basin. This information sets the yardstick to restoration of the hydrological and environmental health of the basin and can lead to better management and planning of water resources under scarcity.

The assessment of climate upon the hydrologic response is crucial for decision-makers to accomplish various adaptation strategies. While, the availability of finer scale projections from regional climate models (RCM) has been a boon to study changing climate conditions, these climate models are subjected to large number of uncertainties, which demands a careful selection of an appropriate climate model, however. In an effort to account for these uncertainties and select suitable climate models, a multi-criteria ranking approach is deployed in this study. Ranking of CORDEX RCMs is done based on its ability to generate hydrologic components of the basin, i.e., runoff simulations using SWAT model, by deploying Entropy

and PROMETHEE-2 methods. The spatial extent of changes in the different components of hydrologic cycle is examined over the Ganga River basin, using the top three ranked RCMs, for a period from January 2021 to December 2100. It is observed that for monsoon months (June, July, August and September), future annual mean surface runoff will decrease substantially (-50 % to - 10%), while the flows for post-monsoon months (October, November and December) are projected to increase (10- 20 %). While, extremes are seen to be increasing during the non-monsoon months, a substantial decrease in medium events is also highlighted. The increase in wet extremes is majorly supplemented by the increased snowmelt runoff during those months. Snowmelt is projected to increase during the months of November to March, with the month of December witnessing 3-4 times increase in the flow. Base flow and recharge are alarmingly decreasing over the basin.

For the development of sustainable water resource strategies, it is essential to establish interaction between landuse changes and local hydrology through proper assessment. Precisely, seeing how change in each LULC affects hydrologic regimes, or conversely evaluating which LULC shall be appropriate for the local hydrological regime can help decisionmakers to incorporate in the policy instruments. In this study, hydrologic regimes of the Ganga River basin have been assessed with landuse change. Simulated streamflow was compared at different gauge stations distributed across the Ganga River and its tributaries. Urbanization has been the topmost contributor to the increase in surface runoff and water yield. While increased irrigation demands were the dominant contributor to the water consumption and also added to the increased evapotranspiration.

There is a need for the development of infrastructure and the necessity for the management of available water resources in a sustainable and economic manner. Reservoirs are recognized as one of the most efficient infrastructure components in integrated water resources management. To achieve optimal reservoirs operating policies, a considerable amount of optimization and

simulation models have been introduced in the course of recent years. Subsequently, the assessment and estimation that is associated with the operation of reservoir stays conventional. In the present study, the Soil and Water Assessment Tool models and a Genetic Algorithm model has been employed to two reservoirs in Ganga River basin, India in order to obtain the optimal reservoir operational policies. The rule curves that were estimated via random search have been discovered to be consistent with that of demand requests. Thus, in the present case study, on the basis of the generated result, it has been concluded that GA-derived optimal reservoir operation rules are competitive and promising, and can be efficiently used.

Under climate change and pressure from human activities, extreme flood events are becoming a significant concern. Methodologies to prevent loss of life and alleviating destruction and damage from floods have changed appreciably in last few decades. The study involves setting up a coupled hydroclimate-hydrodynamic models over the Ganga River basin by coupling the CORDEX regional climate models to the physically based Soil Water Assessment Tool-based hydrological model and MIKE 21C-based hydrodynamic model. The coupled model was employed to explore the flood inundation and dynamics of sediment mobilization amid various extreme events under future conditions. The water level, particularly for the 40-year return period for the late century (2061–2100), is estimated to rise in the future (0.9–1.2m). Since extreme streamflow has increased in the future, morphological transformations will also aggravate. Moreover, during the extreme events, the peaks in shear stress and velocity profile distribution have a propensity to coincide with the areas of the meander bend, implying that the river meander processes govern the shifts in the dynamics of the sediment transport. Flood risk management encompasses flood prevention with possibly strong countermeasures, but also requires communities to learn to live with floods and stakeholders who live in flood-prone areas in order to develop surviving strategies and subsequently enhance their resilience to reduce the flood risk when they occur. The present study focusses on the impact of various

alleviation strategy on the water level of the river. In the present study, various structural as well as non- structural alleviation schemes for reducing the impact of the flood risk in the Ganga River basin and its tributaries have been recommended. Based on the analysis, several structural and non-structural measures are recommended that could be implemented to alleviate river flood problems as well as urban flooding in the basin.

The present study offers a more reliable regional hydrologic impact assessment with quantifications of future dramatic changes in different hydrological sub-system and its mass-transfer, which will help in quantifying the changes in hydrological components in response to climate change changes in the major basin Ganga, and shall provide the water managers with substantive information, required to develop ameliorative strategies. The study could be an important tool in quantifying the changes in hydrological components in response to changes made in landuse, especially for basins undergoing rapid commercialization. The recommendations suggested in the study could be helpful in guiding stakeholders and decision makers in developing and employing sustainable flood management schemes to enhance flood resilience. This shall provide substantive information to the decision makers required to develop ameliorative strategies.

Keywords: Surface water modelling; SWAT; Ganga River basin; Hydrologic modelling; Trend test; Landuse and Landcover (LULC) change; Urbanization; Climate change; Landuse change; CORDEX; Regional Climate Models (RCM); reservoir operation; Genetic Algorithm; Hydrodynamic; MIKE 21C

सारांश

गंगा नदी बेसिन दुनिया में सबसे अधिक आबादी वाली नदी प्रणालियों में से एक है। गंगा और उसकी सहायक नदियों द्वारा कृषि, पीने, जलविद्युत उत्पादन, नेविगेशन और पारिस्थितिक तंत्र सेवाओं के लिए प्रदान किए जाने वाले पानी के आधार पर प्रत्यक्ष या अप्रत्यक्ष रूप से अनुमानित 440 मिलियन लोगों के साथ नदी का अत्यधिक महत्व है। सतत जनसंख्या वृद्धि और परिणामी जल संसाधनों के विकास ने नदी के प्रवाह शासन को प्रभावित किया है, जिसने बदले में, पानी की उपलब्धता, पानी की गुणवत्ता और इस प्रकार, नदी के पारिस्थितिक तंत्र को प्रभावित किया है।

सिंचाई प्रणाली, खाद्य सुरक्षा और पारिस्थितिक तंत्र के स्वास्थ्य के लिए पानी की उपलब्धता एक पेचीदा मुद्दा बन गया है। ताजा पानी की उपलब्धता को एक वैश्विक मुद्दे के रूप में मान्यता दी गई है, और पानी के स्थायी प्रबंधन को मजबूत करने के लिए अलग-अलग बेसिन के भीतर इसका विश्वसनीय मूल्यांकन और मात्रा का आकलन आवश्यक है। इसके अलावा, जलवायु परिवर्तन के नकारात्मक प्रभावों को स्थानिक पैमाने की विस्तृत श्रृंखला पर महसूस किया गया है, जिसमें छोटे बेसिन से लेकर बड़े वाटरशेड तक शामिल हैं, जो संभवतः उन सेवाओं के लिए हानिकारक हो सकते हैं जो प्राकृतिक जल प्रणाली, समाज को प्रदान करती हैं। इसके अलावा, बढ़ते सिंचित कृषि क्षेत्र, वाणिज्यिक फसलों, स्थानांतरित खेती और लगातार बढ़ती घरेलू और औद्योगिक मांग के बीच संघर्ष, पहले से ही गंगा नदी बेसिन, भारत में तनाव का कारण रहा है। वर्तमान में, सामाजिक अर्थव्यवस्था की निरंतर प्रगति और पानी की आवश्यकता के साथ, जल संसाधनों की कमी की समस्या विकराल हो गई है, और बाढ़ के पानी की खपत के मामले में जलाशयों का संचालन महत्वपूर्ण रूप से महत्वपूर्ण हो गया है।

जल संसाधनों के नियोजन और प्रबंधन के लिए भौतिक आधारित हाइड्रोलॉजिकल मॉडलिंग का अनुप्रयोग अनिवार्य हो गया है। हालांकि, इन मॉडलों को विभिन्न वाटरशेड प्रबंधन प्रथाओं के परिदृश्य निर्माण और मूल्यांकन के लिए आगे उपयोग करने से पहले कैलिब्रेट और मान्य करने की आवश्यकता

है। इस अध्ययन में, गंगा नदी बेसिन के लिए Soil and Water Assessment Tool मॉडल का उपयोग करके बेसिन-स्केल हाइड्रोलॉजिकल मॉडल विकसित किया गया है ताकि विभिन्न हाइड्रोलॉजिकल प्रक्रियाओं का अनुकरण किया जा सके। प्रेक्षित डिस्चार्ज श्रृंखला का उपयोग करते हुए मॉडल सत्यापन ने दिखाया कि simulated discharge की मौसमी गतिशीलता observed डेटा के अनुरूप थे और यह सुझाव देते हैं कि मॉडल गंगा नदी बेसिन की मुख्य जल विज्ञान विशेषताओं को पुनः उत्पन्न करने में सक्षम है जिसमें बर्फ और ग्लेशियर पिघलना शामिल है। अध्ययन ने संकेत दिया कि पूरे बेसिन की वार्षिक औसत वर्षा, शुद्ध जल उपज और वास्तविक वाष्पीकरण क्रमशः 1,167.5 मिमी, 601.6 मिमी और 496.5 मिमी थे। हालांकि, इन घटकों के अस्थायी और स्थानिक वितरण दोनों में बड़े अंतर हैं। सांख्यिकीय विधियों (the Mann-Kendall, the Spearman's Rho, and the Student's t) का उपयोग गंगा नदी बेसिन और उसके उप-घाटियों पर स्वाट मॉडल का उपयोग करके simulated प्रवाह में प्रवृत्तियों और भयानक परिवर्तन का पता लगाने के लिए किया गया है। यह पाया गया है कि हालांकि बेसिन के बर्फीले क्षेत्रों से और बेसिन के अंतिम आउटलेट (अध्ययन में फरक्का में लिया गया) से प्रवाह में वृद्धि हुई है, जबकि निचली नदियों और गैर-बारहमासी सहायक नदियों के धारा प्रवाह में उल्लेखनीय रूप से गिरावट आई है। इस गिरावट के लिए मानवजनित गतिविधियों और बहिर्जात परिवर्तनों, दोनों को जिम्मेदार ठहराया जा सकता है। अध्ययन इंगित करता है कि बेसिन में virgin परिदृश्य के संबंध में समग्र जल संसाधनों की उपलब्धता में पर्याप्त कमी आई है। यह जानकारी बेसिन के जल विज्ञान और पर्यावरणीय स्वास्थ्य की बहाली के लिए मानदंड निर्धारित करती है और कमी के तहत जल संसाधनों के बेहतर प्रबंधन और योजना की ओर ले जा सकती है। विभिन्न अनुकूलन रणनीतियों को पूरा करने के लिए निर्णय लेने वालों के लिए जल विज्ञान प्रतिक्रिया पर जलवायु का आकलन महत्वपूर्ण है। हालांकि, regional climate models (RCM) से बेहतर पैमाने के अनुमानों की उपलब्धता बदलती जलवायु परिस्थितियों का अध्ययन करने के लिए एक वरदान रही है, ये जलवायु मॉडल बड़ी संख्या में अनिश्चितताओं के अधीन हैं, जो एक उपयुक्त जलवायु

मॉडल के सावधानीपूर्वक चयन की मांग करते हैं। इन अनिश्चितताओं को ध्यान में रखते हुए और उपयुक्त जलवायु मॉडल का चयन करने के प्रयास में, इस अध्ययन में एक multi-criteria ranking approach का उपयोग किया गया है। CORDEX RCM की रैंकिंग बेसिन के हाइड्रोलॉजिकल घटकों को उत्पन्न करने की क्षमता के आधार पर की जाती है, अर्थात्, SWAT मॉडल का उपयोग करके अपवाह सिमुलेशन, एन्ट्रॉपी और PROMETHEE-2 विधियों को लागू करके। जनवरी 2021 से दिसंबर 2100 की अवधि के लिए, शीर्ष तीन रैंक वाले RCM का उपयोग करते हुए, गंगा नदी बेसिन पर जल विज्ञान चक्र के विभिन्न घटकों में परिवर्तन की स्थानिक सीमा की जांच की जाती है। यह देखा गया है कि मानसून के महीनों (जून, जुलाई, अगस्त और सितंबर) के लिए, भविष्य के वार्षिक औसत सतही अपवाह में काफी कमी आएगी (-50% से - 10%), जबकि मानसून के बाद के महीनों (अक्टूबर, नवंबर और दिसंबर) के लिए प्रवाह (10- 20%) बढ़ने का अनुमान है। जबकि, गैर-मानसून महीनों के दौरान extreme events में वृद्धि देखी जाती है, मध्यम घटनाओं में पर्याप्त कमी को भी उजागर किया जाता है। नवंबर से मार्च के महीनों के दौरान स्नोमेल्ट बढ़ने का अनुमान है, दिसंबर के महीने में प्रवाह में 3-4 गुना वृद्धि देखी जा सकती है। बेसिन के ऊपर बेस फ्लो और रिचार्ज तेजी से कम हो रहे हैं।

स्थायी जल संसाधन रणनीतियों के विकास के लिए, उचित मूल्यांकन के माध्यम से भूमि उपयोग परिवर्तन और स्थानीय जल विज्ञान के बीच संपर्क स्थापित करना आवश्यक है। सटीक रूप से, यह देखते हुए कि प्रत्येक LULC में परिवर्तन, हाइड्रोलॉजिकल व्यवस्थाओं को कैसे प्रभावित करता है, या इसके विपरीत मूल्यांकन करना कि स्थानीय हाइड्रोलॉजिकल regime के लिए कौन सा LULC उपयुक्त होगा, नीति निर्माताओं को नीति उपकरणों में शामिल करने में मदद कर सकता है। इस अध्ययन में भूमि उपयोग परिवर्तन के साथ साथ, गंगा नदी बेसिन की जल विज्ञान व्यवस्थाओं का मूल्यांकन किया गया है। गंगा नदी और उसकी सहायक नदियों में वितरित विभिन्न गेज स्टेशनों पर simulated धारा प्रवाह की तुलना की गई। सतही धारा प्रवाह और जल yield में वृद्धि में शहरीकरण का सबसे

बड़ा योगदान रहा है। जबकि बढ़ी हुई सिंचाई मांगों ने पानी की खपत में प्रमुख योगदान दिया और वाष्पीकरण में वृद्धि को भी जोड़ा।

बुनियादी ढांचे के विकास और उपलब्ध जल संसाधनों के टिकाऊ और आर्थिक तरीके से प्रबंधन की आवश्यकता है। जलाशयों को एकीकृत जल संसाधन प्रबंधन में सबसे कुशल बुनियादी ढांचे के घटकों में से एक के रूप में मान्यता प्राप्त है। इष्टतम जलाशय संचालन नीतियों को प्राप्त करने के लिए, हाल के वर्षों के दौरान काफी मात्रा में अनुकूलन और अनुकरण मॉडल पेश किए गए हैं। जलाशय के संचालन से जुड़ा मूल्यांकन और अनुमान पारंपरिक रहता है। वर्तमान अध्ययन में, इष्टतम जलाशय संचालन नीतियों को प्राप्त करने के लिए, भारत के गंगा नदी बेसिन में दो जलाशयों के लिए Soil and Water Assessment Tool मॉडल और एक Genetic एल्गोरिथम मॉडल को नियोजित किया गया है। यादृच्छिक खोज के माध्यम से अनुमानित rating curves को मांग अनुरोधों के अनुरूप पाया गया है। इस प्रकार, वर्तमान मामले के अध्ययन में, उत्पन्न परिणाम के आधार पर, यह निष्कर्ष निकाला गया है कि Genetic एल्गोरिथम व्युत्पन्न इष्टतम जलाशय संचालन नियम प्रतिस्पर्धी और आशाजनक हैं, और कुशलतापूर्वक उपयोग किया जा सकता है।

जलवायु परिवर्तन और मानवीय गतिविधियों के दबाव में, अत्यधिक बाढ़ की घटनाएं एक महत्वपूर्ण चिंता का विषय बनती जा रही हैं। पिछले कुछ दशकों में जानमाल के नुकसान को रोकने और बाढ़ से होने वाले नुकसान और नुकसान को कम करने के तरीकों में काफी बदलाव आया है। अध्ययन में CORDEX क्षेत्रीय जलवायु मॉडल को भौतिक रूप से आधारित Soil and Water Assessment Tool मॉडल आधारित हाइड्रोलॉजिकल मॉडल और MIKE 21C-आधारित हाइड्रोडायनामिक मॉडल के साथ जोड़कर गंगा नदी बेसिन पर एक युग्मित हाइड्रोक्लाइमेट-हाइड्रोडायनामिक मॉडल स्थापित करना शामिल है। भविष्य की परिस्थितियों में विभिन्न extreme events के बीच बाढ़ जलप्लावन और तलछट की गतिशीलता का पता लगाने के लिए युग्मित मॉडल को नियोजित किया गया था। जल स्तर, विशेष रूप से 40 साल की return period के लिए late century (2061-

2100) में बढ़ने (0.9-1.2 मी) की सम्भावना है। चूंकि भविष्य में चरम प्रवाह में वृद्धि हुई है, morphological परिवर्तन भी बढ़ेंगे। इसके अलावा, extreme events के दौरान, peaks in shear stress और velocity profile वितरण में मेन्डर मोड़ के क्षेत्रों के साथ मेल खाने की प्रवृत्ति होती है, जिसका अर्थ है कि नदी की मेन्डर प्रक्रियाएं तलछट परिवहन की गतिशीलता में बदलाव को नियंत्रित करती हैं। बाढ़ जोखिम प्रबंधन में संभावित रूप से मजबूत प्रति-उपायों के साथ बाढ़ की रोकथाम शामिल है, लेकिन इसके लिए समुदायों को बाढ़ के जोखिम वाले क्षेत्रों में रहने वाले हितधारकों और हितधारकों के साथ रहना सीखना होगा ताकि जीवित रणनीतियों को विकसित किया जा सके और बाढ़ में बाढ़ के जोखिम को कम करने के लिए उनके लचीले पन को बढ़ाया जा सके। वर्तमान अध्ययन नदी के जल स्तर पर विभिन्न उपशमन रणनीति के प्रभाव पर केंद्रित है। वर्तमान अध्ययन में गंगा नदी बेसिन और उसकी सहायक नदियों में बाढ़ के जोखिम के प्रभाव को कम करने के लिए विभिन्न संरचनात्मक और गैर-संरचनात्मक उपशमन योजनाओं की सिफारिश की गई है। विश्लेषण के आधार पर, कई संरचनात्मक और गैर-संरचनात्मक उपायों की सिफारिश की जाती है जिन्हें नदी बाढ़ की समस्याओं के साथ-साथ बेसिन में शहरी बाढ़ को कम करने के लिए लागू किया जा सकता है।

वर्तमान अध्ययन विभिन्न हाइड्रोलॉजिकल सब-सिस्टम और इसके बड़े पैमाने पर स्थानांतरण में भविष्य के नाटकीय परिवर्तनों की मात्रा के साथ एक अधिक विश्वसनीय क्षेत्रीय हाइड्रोलॉजिकल प्रभाव मूल्यांकन प्रदान करता है, जो गंगा बेसिन में जलवायु परिवर्तनों के जवाब में हाइड्रोलॉजिकल घटकों में परिवर्तन को मापने में मदद करेगा, और जल प्रबंधकों को सुधारात्मक रणनीति विकसित करने के लिए आवश्यक वास्तविक जानकारी प्रदान करेगा। भू-उपयोग में किए गए परिवर्तनों के जवाब में, विशेष रूप से तेजी से व्यावसायीकरण के दौर से गुजर रहे बेसिन के लिए, हाइड्रोलॉजिकल घटकों में परिवर्तन की मात्रा निर्धारित करने में अध्ययन एक महत्वपूर्ण उपकरण हो सकता है। अध्ययन में सुझाई गई सिफारिशें, हितधारकों और निर्णय निर्माताओं को बाढ़ के प्रतिरोध को बढ़ाने के लिए स्थायी बाढ़ प्रबंधन योजनाओं को विकसित करने और नियोजित करने में मार्गदर्शन करने में सहायक हो सकती हैं। यह

सुधारात्मक रणनीतियों को विकसित करने के लिए आवश्यक निर्णय निर्माताओं को वास्तविक जानकारी प्रदान करेगा।

खोजशब्द: सतही जल मॉडलिंग; SWAT; गंगा नदी बेसिन; हाइड्रोलॉजिकल मॉडलिंग; रुझान परीक्षण; लैंडयूज और लैंडकवर (LULC) परिवर्तन; शहरीकरण; जलवायु परिवर्तन; भूमि उपयोग परिवर्तन; CORDEX; Regional Climate Models (RCM); जलाशय संचालन; Genetic Algorithm; हाइड्रोडायनामिक; MIKE 21C

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